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PRINCIPLES FOR THE EXECUTION OF TENSILE AND CREEP TESTS IN VACUUM AT HIGH TEMPERATURES

F. Bollenrath, H. Feldmann, G. Happek

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PRINCIPLES FOR THE EXECUTION OF TENSILE AND CREEP TESTS IN VACUUM AT HIGH TEMPERATURES

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ABSTRACT. The present state of development of the methods used for various tests for tensile and creep studies at high temperatures in vacuum, characterized by research devices and procedures which often permit no direct comparison of the research results. For its evaluation the sources of error of the method must be known. The research conditions of vacuum, power initiation, expansion measurements, expansion rate, temperature, and temperature distribution were studied. The pressure in the vacuum chamber and the leak rate should be considerable for the research materials. Inhomogeneous deformations distributed over the sample cross section and measurement length, relative motions between sample and test machine or expansion measurement device, and temperature expansion could not be detected individually and were eliminated. The power initiation in the vacuum chamber and the sample must be followed so that additional stresses remain as low as possible. The expansion rate of the measurement length was strongly affected by the shape of the test device at constant escape rate of the traverse. The drive must therefore be so operated that the expansion rate in the measurement gap remains constant. An accurate expansion measurement is necessary during the tensile studies for the expansion rate control. Elasticity and expansion limits were determined higher at constant expansion rate at room temperature than at constant stress rate of the traverse. The effect of the temperature deviations in the measurement length on the material characteristics was described. For evaluation of the measurement methods, test norms, and materials and for the measurement of constituents it is necessary to know how reliable the resistance characteristics are. The relative resulting stress error is given as a function of the affecting parameters (expansion, temperature, expansion rate) and dimensionless error moduli. Properties determined in tensile and creep studies of various work materials are reported. 4415

State of Technology

Experience gained in tensile and creep testing in air up to 1000°C is very /998
extensive. Despite this fact, thorough investigation reveals that various
factors have not been adequately considered in the performance of the tests /999
and that these are not generally controlled; let us mention, e.g., the effect

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* Numbers in the margin indicate pagination of the foreign text.

of the deformation of the testing machine and the ends of the specimen on tensile values and problems of the accuracy of temperature and strain measurements in creep testing 1-8 . At temperatures above approximately 1000°C and in vacuo, testing becomes more difficult [9, 10].

In recent years, great efforts have been expended in order to improve and to develop the technology of high-temperature testing. Upon recommendation of the Structures and Materials Panel of AGARD (Advisory Group for Aerospace Research and Development, NATO), the behavior of TZM molybdenum was determined in tensile testing to 1800°C, in comparative testing by 11 laboratories. The great deviations in test results of the different laboratories, made it necessary to investigate the effect of the individual factors closer in additional work [11]. Special emphasis was placed on the following testing conditions: vacuum, specimen configuration, strain measurement, strain rate and temperature. Additional aggravating conditions occur in creep testing.

In the following, certain aspects of the conduct of such experiments at elevated temperatures will be discussed. In addition, the effect of measuring and control errors on property values will be treated.

Experimental Conditions

Vacuum

High-melting metals and their alloys are subject to very vigorous oxidation in air at temperatures in excess of 450 to 650°C so that tests must be performed in a neutral atmosphere or preferably in a high vacuum.

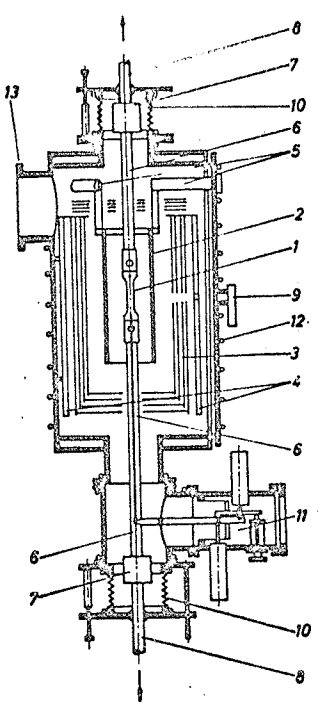
The quality of the vacuum cannot be characterized adequately by citing the pressure, because the leak rate also affects the contamination of the materials. The real and apparent components of the leak rate should be known, in order to distinguish between air coming in because of inadequate sealing and the gas yield due to the degassing of container walls, the recirculation of propellants, etc. If such components are difficult to identify, the recording of the pressure-time behavior in the vacuum chamber after inactivation of the pump is recommended.

The necessary vacuum conditions must be established in each case, because they are governed by the material (vapor pressure of alloying components and

oxides, internal oxidation, etc.), the configuration of specimens and their arrangement in the furnace, the temperature and duration of the test. At a testing temperature of 1095°C and a test time of 1522 hours, e.g. the oxygen absorption of the FS 85 Nb alloy (28 Ta, 9.5 W, 0.8 Zr, 0.018 O_2, by weight %) /100
in a vacuum of 2 x 10^{-7} torr (start) and 4 x 10^{-9} torr (end) amounted to 62 ppm [12]. On the other hand, Nb is extensively degassed in a vacuum of approximately 10^{-6} at 2300°C [13].

Introduction of Forces in the Vacuum Chamber and the Specimen

The problem of introducing the force in the vacuum chamber may be circumvented by placing the entire testing machine in vacuum. This solution is recommended mainly for creep testing of long duration because the testing machine is relatively small, may be built without locations to be lubricated and stressed by weights. NASA performs creep tests in suitable test installations under very high vacuum [12].



1 - tensile test specimen
2 - resistance heating elements (tungsten web, 200 mm long, 50 mm in diameter)
3 - protective sheets against radiation
4 - cooling jacket
5 - water-cooled power inlets
6 - drawbars
7 - threaded connection
8 - water-cooled drawbars
9 - quartz glass window for optical temperature measurements
10 - metal bellows
11 - strain measuring instrument
12 - cooling coils
13 - flange of diffusion pump

Figure 1. Marshall furnace (diagram).

In tensile testing, the force is introduced in the evacuated furnace generally either with the aid of a metallic bellows or a stuffing box. In the latter case, the strain gage for force measurements must also be mounted in the vacuum chamber. This introduces additional potential errors in force measurement. Intensive cooling of drawbars in the furnace space is required /100
so that the temperature distribution along the specimen is affected in an unfavorable manner. For this reason, in the author's experimental apparatus, the force was introduced preferably by way of bellows, as in the Marshall high-temperature furnace. The furnace is shown in Figure 1 and described in detail in [10]. In force measurements, depending on the atmospheric pressure, vacuum and spring forces must be considered. A similar furnace installation proved to be suitable for creep testing [9]. A disadvantage of the bellows design is the fact that according to the centering of the furnace in the test machine, different transverse forces may act on the drawbars; they are difficult to control, the difficulty being enhanced by the variation of the centering with temperature.

Measures to insure centered force introduction in the specimen and the effects of additional stresses on the configuration of the stress-strain diagram were discussed in detail in the literature [6, 9, 10, 14, 15]. The effectiveness of ball and socket and pivot joints at the ends of the drawbars is greatly restricted by the self-locking of the bearings. The latter occurs when the line of action of the force contacts the friction circle with a radius of μr (μ - coefficient of friction, r - radius of the ball or pivot). With $\mu \approx 0.1$ and $r \approx 50$ mm, the radius of the friction circle is of an order of magnitude of 5 mm.

An estimate of the bending momentum distribution in the drawbars is given in Figure 2 for certain types of loading and bearing. Even in the case of direct weight loading by way of a "frictionless" joint, e.g. in creep machines, large bending momentums may occur in the specimen, if the upper end of the drawbar is supported in a socket (Figure 2a). If after ideal alignment of the drawbars and the specimen in the joints self-locking occurs at the ends of the drawbars, bending momentum behavior in accordance with Figure 2b will take place, if the rod is further strained. With excentric tensile specimens having /100

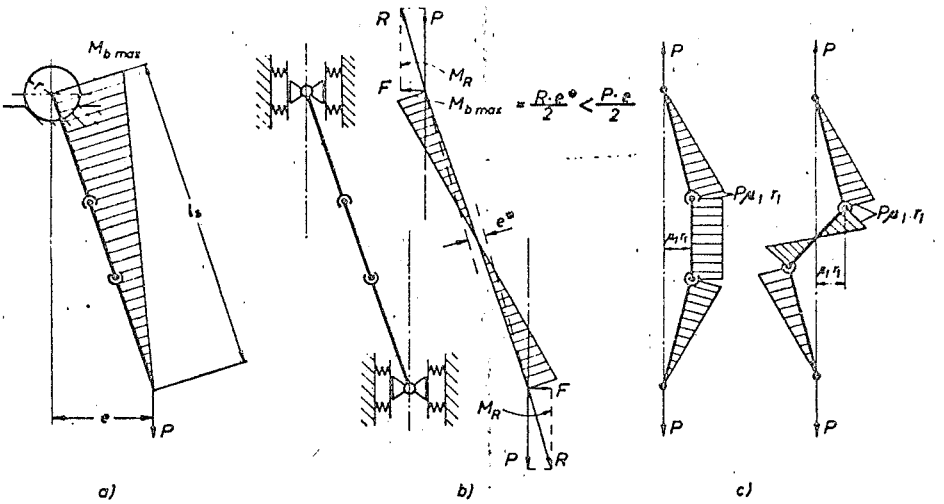


Figure 2. Estimation of bending momentum distribution in the drawbars.

an excentricity of 7 mm, a change in signs of the bending stress was observed in the measured distance if the frictional moments at the end of the drawbars were sufficiently large [14]. Rigidly supported drawbars, well centered in the machine and the furnace are obviously of advantage. In the case of an ideal geometry of the specimen and the drawbars, frictionless support of the ends, as approximately attained with knife edge bearings, for example, is better, however. The bending moment is then zero over the entire drawbar system; also, changes in the excentricity of the machine frame is compensated for during the test, involving, however, simultaneous motion of the specimen with respect to the machine. Within the drawbar system, however, a certain excentricity always exists, especially if the specimen is connected with pins with the clamping fixtures, so that a bending moment behavior in accordance with Figure 2c must be expected. Figure 3 is a plot of the relationship of bending to tensile stresses, for flat and round specimens, as a function of excentricity.

Specimen Configuration and Strain Measurements

In high-temperature testing in vacuum the known methods for the measurement of strain independently of extraneous stresses and the relative motion of the specimen with respect to the test machine and the furnace, can be applied in part only. The physical measurement of strain required is not possible at the present time and the reference point of the measurement is not located on the specimen. A change in excentricity within the machine frame during the loading of the specimen and the reversal in direction of the drawbar is

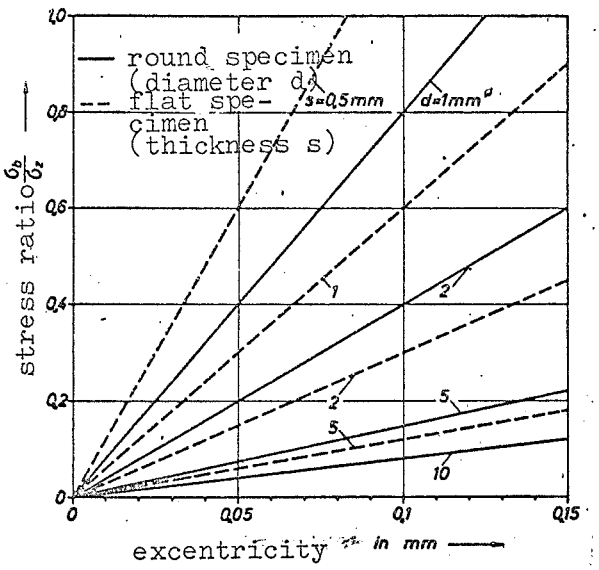


Figure 3. Superposed bending stress with excentric tensile force.

therefore detrimental, apart from extraneous stresses. The accuracy of the determination of the elastic modulus, the elastic limit and the yield point and of the hysteresis loop is strongly affected by such processes. Testing of mechanical testing machine prototypes showed a displacement of the drawbar perpendicularly to the tensile direction by a distance up to 0.5 mm. In a tensile machine of special design this displacement was reduced to about 10 µm. In addition, a precision strain gage is being developed, which is placed directly on the measured length of the specimen and thus moves with the specimen in the manner of the room temperature test instruments. Initially, tests on protectively coated specimens in air with induction heating to 2000°C are scheduled, later, tests in vacuum are to follow.

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A and B universal spring joints
C and D spring joints
E differential transformer for precision strain gage
F differential transformer for coarse strain gage
I and II lever
direction of pull

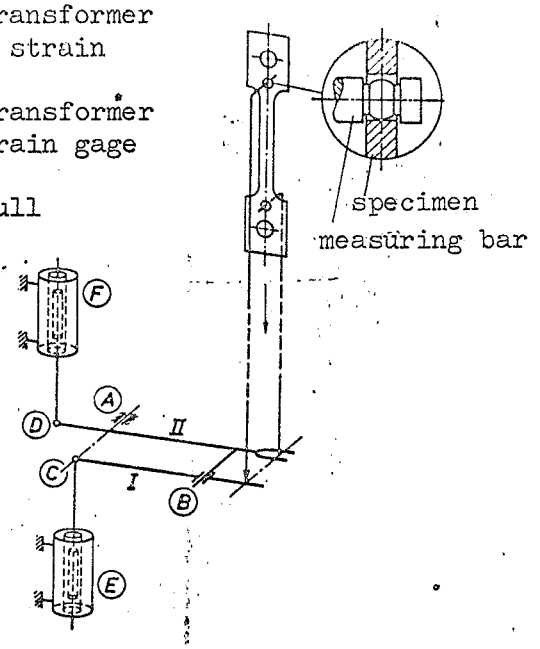

Figure 4. Diagram of strain gage installation.

Since high-temperature materials frequently are difficult to work, the specimen configuration must be especially suitable with consideration of the strain gage type to be used. Suitable specimen shapes are given in [9, 10, 15]. With the presently known strain gages the fastening of measuring rails with knife edges must be abandoned at very high temperatures, due to the lack of suitable edge materials. The specimens thus are frequently made with measuring shoulders. These, however, are difficult to produce on flat specimens, they interfere with the stress and deformation field of the gage length and thus affect the behavior of the material, as discussed in more detail in [16]; in /100
the case of thin sheets therefore spot-welded strip specimens are often preferred. In the author's investigation, the specimen configuration shown in Figure 4 proved to be of advantage. The figure displays in diagram form the strain gage arrangement selected; it also proved to be suitable for round specimens and compression testing with precision strain gages. The immersion core of the differential transformer is in the vacuum, the coil in the air. The error caused by the fact that the cross section is not the same over the entire gage length can be corrected through suitable strain relationships with adequate accuracy [10].

Commercially available strain gages with mechanical strain sensing are equipped with other sensing levers which also compensate for thermal expansion and linkage deformation in the tensile direction, but do not have the simple construction and suspension of the author's apparatus. Mounting on the furnace housing is common to all of the gages, so that the alignment of the draw linkage must be satisfactory. The setup is centered if the drawing linkage does not shift under load transversely to the tensile direction. This is verified easily with dial indicators.

Optical methods of precision strain gage measurements with continuous recording are not sufficiently tested at high temperatures and are rather expensive.

Strain Rate

The variation of the stress σ over the strain $\epsilon = \Delta L_o / L_o$ (ΔL_o elongation of the gage length L_o) is, as is known, a function of the strain rate $\dot{\epsilon}$. For this reason, the testing machines are built rigidly in the tensile direction

and usually designed to that the pull rate of the drawbar $\dot{s}$ is constant in good approximation. The loading of the specimen causes the deformation of the test length L_v with the gage length L_o, the specimen ends including displacements with respect to the clamping parts, and the test machine itself.

Thus at constant drawing rates $\dot{s}$ the strain rate in the range of elastic deformation of the gage length ($\delta\sigma/\delta\varepsilon = E$, modulus of elasticity(is in part substantially less (by about an order of magnitude) than after larger plastic deformations ($\delta\sigma/\delta\varepsilon \approx 0$). At the lower yield point and maximum loads ($\delta\sigma/\delta\varepsilon = 0$) the average strain rate of the gage length ΔL_v ($\Delta L_v > \Delta L_o$) is approximately equal to $\dot{s}$. Equality of ΔL_v and $\dot{s}$ is not attained, because even with constant loads permanent deformation of the testing machine (settling, alignment), motion between the specimen and the clamping fixture and plastic deformation, including creep in the ends of the specimen, occur. After passing through the maximum load point ($\delta\sigma/\delta\varepsilon < 0$), recoil of the test machine is superposed on the displacement of the drawbar so that strain rates can increase substantially. In Figure 5 the equivalent circuit diagram of a tensile testing machine with a specimen is shown. Even in the case of constant draw rate of the /100
drawbar, the configuration of the stress-strain diagram becomes dependent - upon the onset of plastic deformation - on the resiliency of the test machine and the ends of the specimens [1-5, 7, 10]. Constant strain rates can be attained only if the strain - both in precision and coarse measurements - is measured directly on the specimen and the drive of the testing machine is controlled by this signal, so that $\dot{\Delta L}_o$ and $\dot{\varepsilon}$ acquire the proper value. The extent to which the draw rate of the drawbar must be varied in the case of constant strain rates is shown in Figure 6. The drive in this case was controlled manually so that a linear strain-time dependence corresponding to $\dot{\varepsilon} = 0.5\%\ \text{min}^{-1}$ was obtained. Since the mechanical properties of high-melting metals, among others, depend strongly on the strain rate - Figure 7 - high-temperature tensile tests require such a machine if the test results of different laboratories are to /100
be comparable directly to each other. For this reason, in cooperation with a manufacturer of testing machines, an electromechanical drive control was developed which permits, even with a "soft" testing apparatus generally present at elevated temperatures and with strong variations of the tangent modulus $\delta\sigma/\delta\varepsilon$ in the transition from the elastic to the elastic-plastic deformation range, to maintain

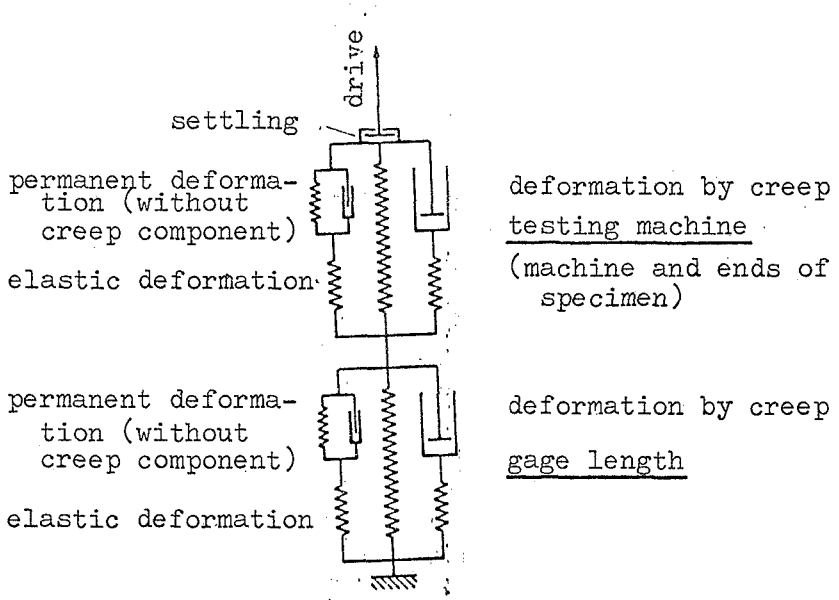

Figure 5. Equivalent circuit diagram of a tensile testing machine with specimen.

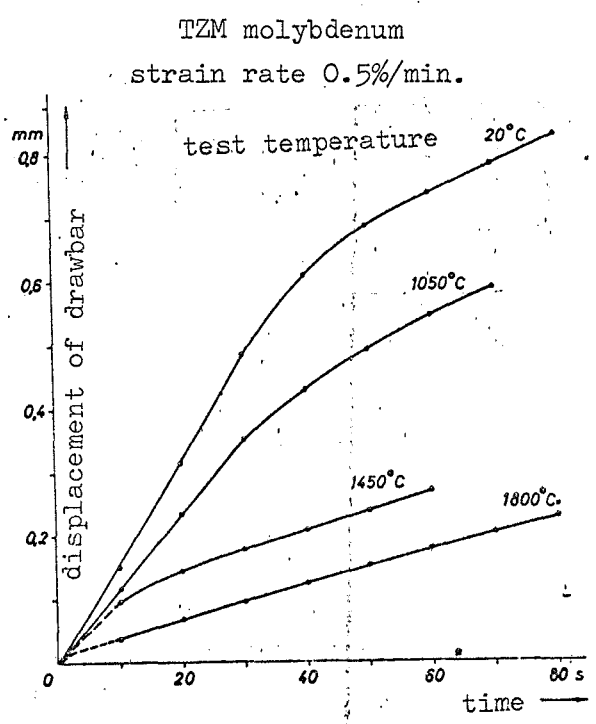

Figure 6. Time dependence of the drawbar displacement at constant strain rates.

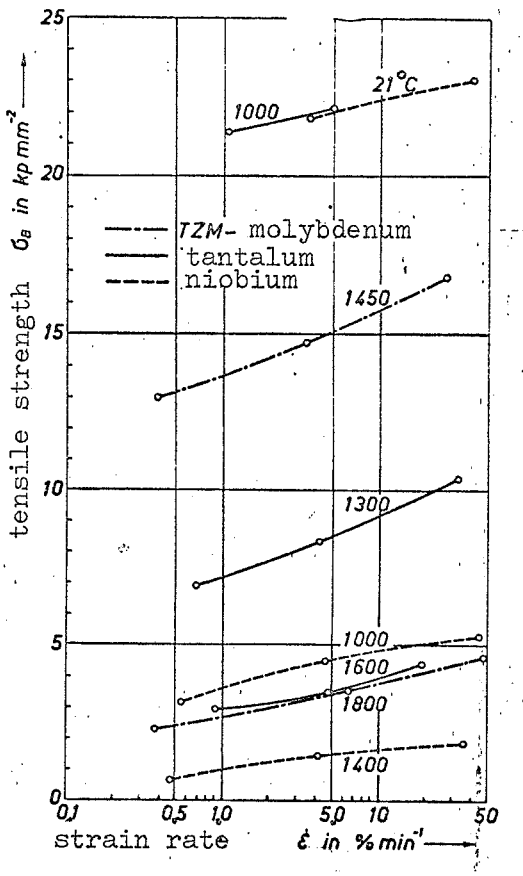

Figure 7. Effect of strain rate on tensile strength.

a constant strain rate $\dot{\epsilon}$ with great accuracy automatically, if no pronounced yield point is present. Following precision strain measurements, the experiment can be continued directly to fracture, so that the elongation at fracture can be determined independently of the deformation of the testing machine.

For unalloyed titanium (3-mm sheet, hardness HV 10 = 195 kp mm^{-2}), the elastic limits and yield points determined at constant strain rates and drawbar velocities, are presented in Figure 8. The elastic limit $\sigma_{0.01}$ is higher by 18% , the $\sigma_{0.2}$ limit higher by 8% at ϵ = constant than with a constant drawing rate of the drawbar. In the case of high-melting metals, greater deviations must be expected at elevated temperatures, Figure 9a and 9b. Precise strain measurement is also necessary with respect to maintenance of strain rate constants.

Temperature

Advantages and disadvantages of the different heating methods (direct and indirect induction or resistance heating, optical beam concentration), together

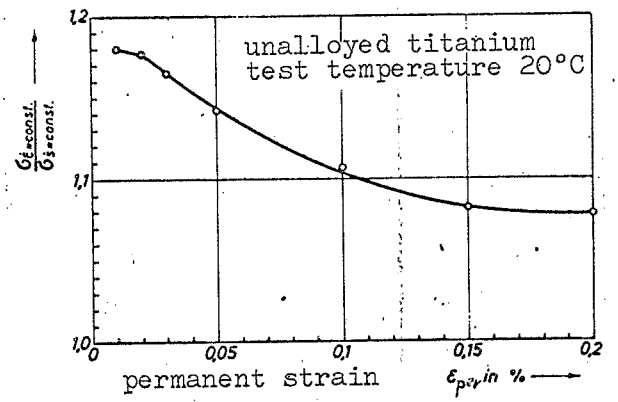

Figure 8. Ratio of yield points determined at a constant strain rate and at constant draw velocity of the drawbar.

$\sigma\varepsilon$ = constant, determined at $\dot{\varepsilon}$ = 0.12% min^{-1}

$\sigma\varepsilon$ = constant, determined at $\dot{\zeta}/L_v$ = 0.12% min^{-1}, L_v = gage length

Testing machine: Testatron, Wolpert.

with temperature measurement problems are described in detail in [8, 9]. Here, /100 only the temperature deviation within the strain gage shall be treated.

In order to attain sufficient accuracy of strain measurements, maximum strain gage lengths are frequencly recommended for high-temperature experiments. The author's investigation showed, however, that with a ratio of the gage length to the heating grid of 1:8, temperature deviations of ±4°C are in part difficult to maintain; it became necessary to instal thermal baffle plates, locally vary /100 the emission system of the drawbar assembly and the thermal resistance of a draw rod increased by reducing its cross section. For the same temperature deviation, substantially more extensive measures were required with a gage length of 50 mm. In addition, the variation of the temperature profile during the test must be observed, because with increasing strains the differences in temperature rise appreciably. Therefore the temperature distribution over the gage length during ductile behavior should be verified immediately preceding fracture also.

Inhomogeneous temperature distribution over the gage length renders the indication of the test temperature uncertain and leads to locally different strain rates so that yield points, tensile strengths, uniform elongations and

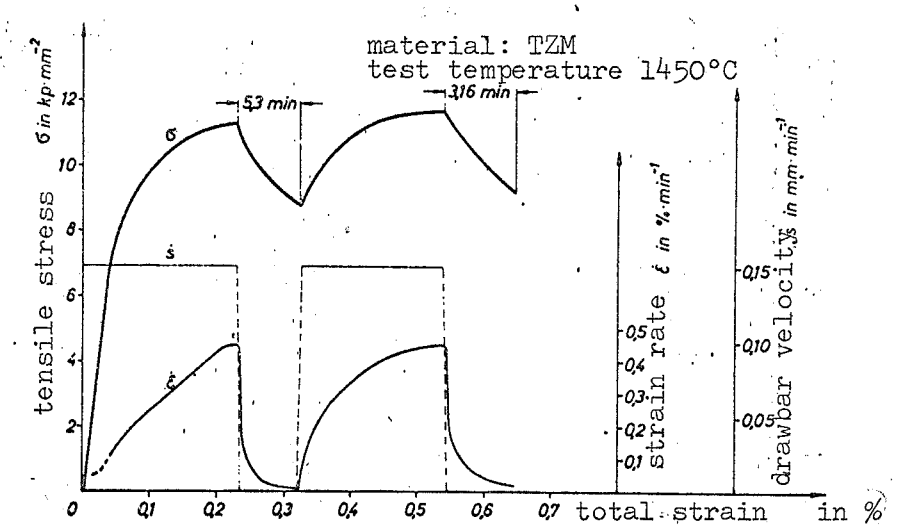

Figure 9a. Tensile and relaxation tests on TZM molybdenum at 1450°C.

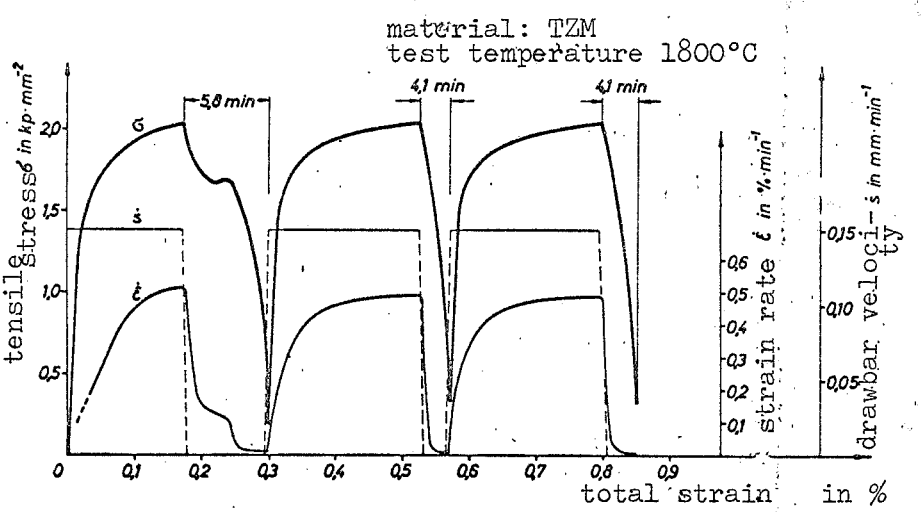

Figure 9b. Tensile and relaxation tests on TZM molybdenum at 1800°C.

elongations at fracture can be strongly affected. Tensile properties rise or decrease in accordance with their dependence on temperature and strain rate and local temperature gradients. The effect of local temperature gradients was investigated on fully annealed TZM molybdenum sheets. At identical mean temperatures of 1450°C (arthimetic mean of temperature at the ends and the center of specimens) and increase in the temperature deviation from ±1.9°C to ±10.7°C,

$\sigma_{0.2}$ varied by approximately +6%, tensile strength by only approximately +2%, and elongation at fracture by approximately -6%. Uniform elongation declined correspondingly so that at a constant nominal strain rate, tensile strength was determined actually at a greater true strain rate.

Estimation of Error[1]

For tensile and creep tests the accuracy of measurements of force, length, time and temperature is extensively defined in the various standards (DIN, ASTM, British Standards, etc.). Permissible errors of these measured values contribute, depending on material behavior, to the inaccuracy of the property to be determined. The property error resulting is of interest for the evaluation of the material and should be known to the designer.

Standard specifications of measuring accuracy are based on extensive experience gained with conventional materials. In the standard testing of such materials and others with similar properties, the resulting error in property values is slight, if the error in the strain rate due to the deformation of the testing equipment is negligible. For testing at temperatures in excess of approximately 1000°C, certain standards do exist with respect to measuring accuracy, they cannot be satisfied in part, and also agreements between testing laboratories, such as the AGARD recommendation contained in the "Cooperative Program on Mechanical Testing of Refractory Metals," which are based on the existing accuracy of the test method. In high-temperature investigations therefore the determination of the partial error resulting from the inaccuracy of measured values is of considerable usefulness, especially if the results of different laboratories are to be compared and measuring methods evaluated and improved. Knowledge of error sources is also required for the establishment of new standard specifications. /1010

The problem of accuracy requirements to be established for values obtained in tensile and creep testing with equal resultant errors in the measured property value is also of great interest; e.g. it is possible to correct in general the error of strain measurement created by including the elongation of specimen shoulders in tensile testing, with sufficient accuracy [10], while according to [18] in creep testing an adequate accuracy of strain measurement can be attained only including equal cross sections in the gage length.

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1. Extensive discussion of error sources is found in 17.

For these reasons, in the following the effect of the measured error on the accuracy of mechanical property values shall be investigated.

Factors

The values measured in tensile testing are lengths, temperature, and time. Since the determination of elongation at fracture and reduction of area at fracture is based only on measurements at room temperature, the error of these measurements will not be discussed in detail at the present time. The error of tensile property measurements caused by the inaccuracy of measured values listed above, will be investigated.

Eq. I gives the resultant relative error of the nominal stress $\delta\sigma/\sigma$ as a function of the relative measuring errors $\delta\varepsilon/\varepsilon$, $\delta T/T$, $\delta\dot{\varepsilon}/\dot{\varepsilon}$ ($\dot{\varepsilon}$ - strain, T - absolute temperature, $\dot{\varepsilon}$ - strain rate) and of dimensionless material properties.

$$\left|\frac{\delta\sigma}{\sigma}\right| = \left|\frac{\delta\sigma_M}{\sigma}\right| + \left|\frac{\partial\sigma/\partial\varepsilon}{\sigma/\varepsilon}\right| \cdot \left|\frac{\delta\varepsilon}{\varepsilon}\right| + \left|\frac{\partial\sigma/\partial T}{\sigma/T}\right| \cdot \left|\frac{\delta T}{T}\right| + \left|\frac{\partial\sigma/\partial\dot{\varepsilon}}{\sigma/\dot{\varepsilon}}\right| \cdot \left|\frac{\delta\dot{\varepsilon}}{\dot{\varepsilon}}\right| \qquad (I)$$

The factors $\left|\frac{\partial\sigma/\partial\varepsilon}{\sigma/\varepsilon}\right|$, $\left|\frac{\partial\sigma/\partial T}{\sigma/T}\right|$ and $\left|\frac{\partial\sigma/\partial\dot{\varepsilon}}{\sigma/\dot{\varepsilon}}\right|$ are designated in the following as the strain, temperature, and strain rate error moduli. $\left|\frac{\delta\sigma_M}{\sigma}\right|$ is the relative nominal stress error due to inaccurate force measurement.

In the linearly elastic range the stress-strain curve is

$$\left|\frac{\partial\sigma/\partial\varepsilon}{\sigma/\varepsilon}\right| = 1 \quad \text{and} \quad \left|\frac{\partial\sigma/\partial\dot{\varepsilon}}{\sigma/\dot{\varepsilon}}\right| \approx 0.$$

By simplification the corresponding stress error (Eq. I) is taken as the error of the yield points. At the highest point of the stress-strain curve, $\left|\frac{\partial\sigma/\partial\varepsilon}{\sigma/\varepsilon}\right| = 0$. The error of strain measurement thus affects the inaccuracy of the tensile strength indirectly only, by way of the strain rate, as shown in the following section. /101

As a rule, constant strain rates are desired in tensile testing. If the necessary control of the velocity of the drawbar is free of error corresponding to the time-dependent strain signal, the strain rate error depends only on the accuracy of strain and time measurements. Slight, short-time deviations from the required value of the strain rate do not affect the configuration of the

force-strain diagram fully because of the response time of the system and may often be taken into consideration subsequently during the evaluation of the work-hardening curve. As a simplification, therefore, the average strain rate $\dot{\epsilon}_m = \epsilon/t$ is being considered. Its relative error is

$$\left|\frac{\delta\dot{\varepsilon}_m}{\dot{\varepsilon}_m}\right| = \left|\frac{\delta\dot{\varepsilon}_R}{\dot{\varepsilon}_m}\right| + \left|\frac{\delta\varepsilon}{\varepsilon}\right| + \left|\frac{\delta t}{t}\right| \qquad (II)^2$$

with the absolute errors

$\delta\dot{\epsilon}_m$ of the average strain rate;
$\delta\epsilon_R$ due to inaccurate control;
$\delta\epsilon$ of strain measurements, and
δt of time.

In tests with constant drawing rate of the drawbar, the strain rate in general increases by several hundred percent during the transition from elastic to elastic-plastic deformation. Deviations of this magnitude lead in the error calculation performed here only to estimates of the error of the property value.

The error of tensile values determined in creep testing may be calculated also by Eq. I. If weight, cross section and time errors are neglected, the following is valid for the accuracy of time-strain limits

$$\left|\frac{\delta\sigma}{\sigma}\right| = \left|\frac{\partial\sigma/\partial\varepsilon}{\sigma/\varepsilon}\right| \cdot \left|\frac{\delta\varepsilon}{\varepsilon}\right| + \left|\frac{\partial\sigma/\partial T}{\sigma/T}\right| \cdot \left|\frac{\delta T}{T}\right| . \qquad (III)$$

The strain error modulus $\left|\frac{\partial\sigma/\partial\varepsilon}{\sigma/\varepsilon}\right|$ cannot be determined directly from the variation with time of strain. Therefore, the total strain and associated stress is taken for the reference time of the time-strain limits (1 hour, 10 hours, 100 hours, etc., for example) from the creep curves [$\epsilon = \epsilon(t)$]. These pairs of values /1012 yield, together with the reference time as a parameter, stress-strain curves from which the strain error modulus can be determined. If time-strain limits with

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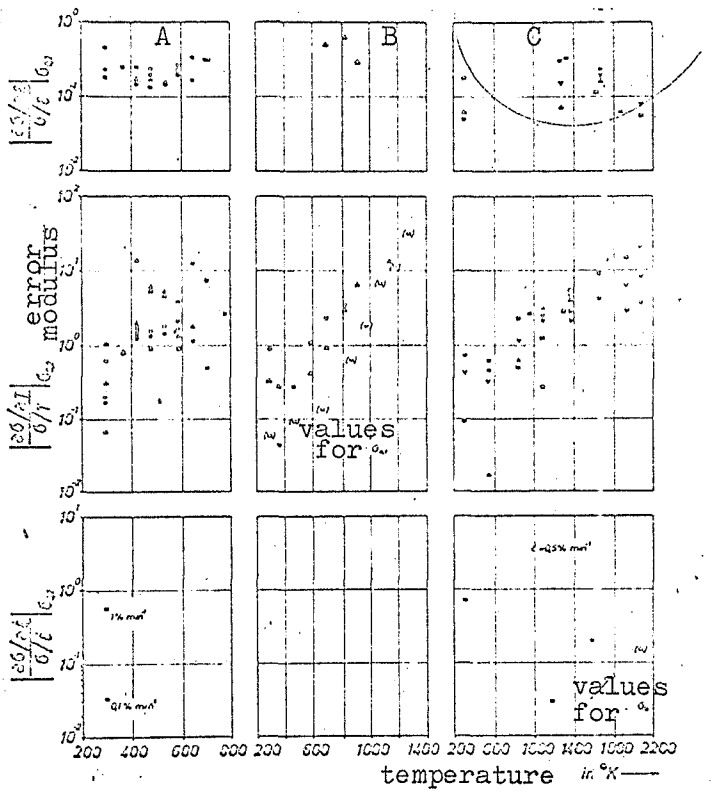
2. Eq. II is equally valid for the instantaneous strain rate if the relative errors of the strain and time differences are introduced on which the determination of $\dot{\epsilon}$ is based. Further, it should be noted that the direct effect of the strain error falsifies the tensile stress in the same sense as the error of the strain rate, which occurs as a result of the strain error.

different reference strains are given, then for different time parameters and temperatures the modulus can be determined from the stress-strain correlation. The accuracy of the creep strength is not affected by the strain error.



A	light metals				B	heat resistant metals		C	high-melting metals				
		Mg	Al	Ti		Nimonic 90				Nb	Ta	Mo	W
	unalloyed	o	▲	o		C steel	▼		unalloyed	○	○	□	▽
	alloyed	o	△	o		Cr-Mo-W-V steel	▲		alloyed	▲	●	■	▼

Figure 10. Temperature dependence of the error moduli for $\sigma_{0.2}$.

Error Moduli and Resulting Stress Errors

Figure 10 presents the error moduli of certain light metals, heat-resistant materials and high-melting metals and alloys as a function of temperature for the $\sigma_{0.2}$ limit. The total strain associated with a permanent elongation of 0.2% was used in the determination of values.

The modulus of strain error is weakly temperature-dependent for the materials/101 investigated. In general, it cannot be greater than 1 and on the average amounts to approximately 1/5. The partial error of $\sigma_{0.2}$ due to the inaccuracy of strain

measurements is thus at the most equal to the relative strain error $|\delta\epsilon/\epsilon|$, without consideration of its effect by way of the strain rate, but on the average is equal to $1/5\ |\delta\epsilon/\epsilon|$.

The error modulus of temperature in part rises strongly with increasing temperatures and in some cases attains values which are clearly above 10. The partial error of the $\sigma_{0.2}$ limit due to temperature inaccuracy thus may exceed the relative error of temperature $|\delta T/T|$ by more than an order of magnitude. The high values of the modulus of temperature error occur not only in the temperature range of large $\partial\sigma/\partial T$, but also with substantially higher temperatures, since then the σ/T ratio becomes less than $\partial\sigma/\partial T$. The average error modulus of temperature is approximately equal to 3. The partial temperature error of the $\sigma_{0.2}$ limit is thus three times as high as the relative error of temperature.

Only a few values of the modulus of strain rate error are available at this time, they indicate that this modulus depends clearly on the strain rate and the temperature. At the customary strain rates in the determination of yield points the value of 1 is probably seldom exceeded; the average is approximately 1/5, as in the case of the strain rate modulus.

At an average dependence of the yield point of the strain, temperature and strain rate, the relative resulting error of $\sigma_{0.2}$ is given as a rough estimate by

$$\left|\frac{\delta\sigma}{\sigma}\right|_{\sigma_{0,2}} \approx 1/5\left|\frac{\delta\varepsilon}{\varepsilon}\right| + 3\left|\frac{\delta T}{T}\right| + 1/5\left|\frac{\delta\dot{\varepsilon}}{\dot{\varepsilon}}\right| \qquad \text{(IVa)}$$

If the draw rate of the drawbar is controlled so that the strain rate is approximately constant, then with consideration of Eq. II

$$\left|\frac{\delta\sigma}{\sigma}\right|_{\sigma_{0,2}} \approx 1/2\left|\frac{\delta\varepsilon}{\varepsilon}\right| + 3\left|\frac{\delta T}{T}\right| \qquad \text{(IVb)}$$

The error moduli of yield points determined in tensile testing are in part substantially less than those of the time-strain limits. This fact became especially pronounced in the case of an AlCuMg aluminum alloy. With increasing reference times of the time-strain limits the error modulus of strain increases strongly and is about 16 times as large at 1000 hours than for the $\sigma_{0.2}$ point in tensile testing. As seen in Figure 11, the conditions are similar for molybdenum.

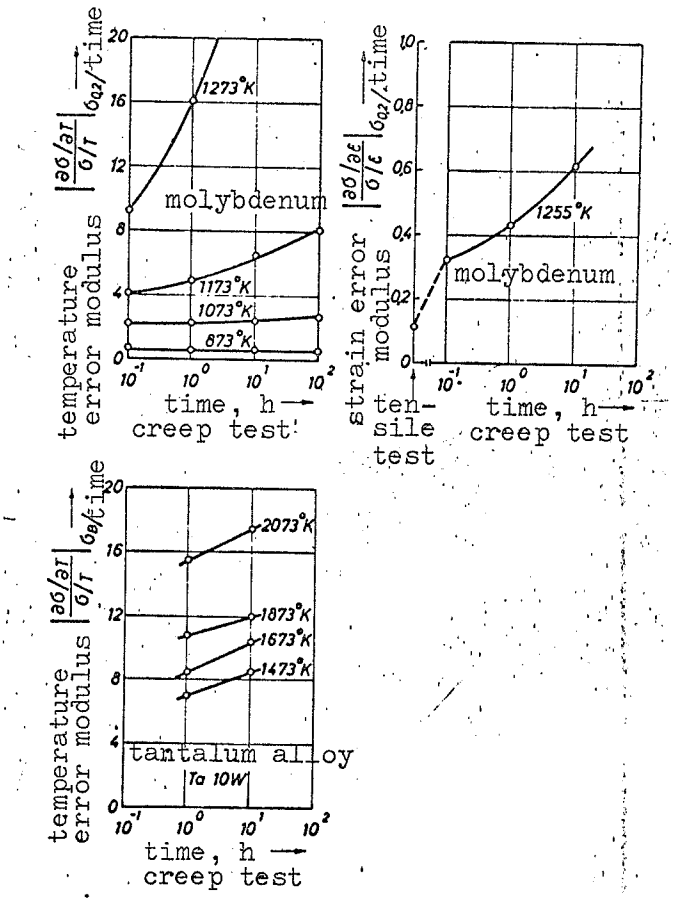


Figure 11. Error moduli of the 0.2 time-strain limit and creep strength.

In general, therefore, the measuring accuracy of strain in creep testing [18] should be higher than in tensile testing [10] . It should be noted, however, that in tensile testing the strain error $|\delta\varepsilon/\varepsilon|$ enters into the error of strain rate and that thus in the case of a clear dependence of the yield points on strain rate an increased effect of $|\delta\varepsilon/\varepsilon|$ on the resulting error of the property value exists (see Eqs. II, III and IV).

The error modulus of temperature as a rule also increases with temperature and time for the time-strain limit and creep strength, Figure 11, and for long periods of time clearly exceeds the values of tensile testing.

The empirically great scatter range of creep strength values for long periods of time is therefore in a large measure due to the inadequate testing techniques employed, in particular due to the error of temperature.

Discussion /1015

D. Dengel, Berlin: Your literature reference in the problem of suspension could create the impression in the auditorium, not entirely correct in my opinion, that the question of suspension for really pure tensile testing has been completely solved. What does your specimen suspension look like?

H. Feldmann, Aachen: The paper placed emphasis on the fact that the ability to function of socket and pin joints can be substantially restricted by self-locking, at the ends of the drawbar system.

The cross section of the tensile specimens investigated by the authors was approximately 10 mm^2 in the gage length. The testing apparatus is thus designed for a maximum load of 1000 kp only. The force is introduced in the drawbar system by way of hardened steel balls with a 3 mm radius. The cup surface on which the ball slides was produced by pressing the ball into a drawbar. The diameter of the indentation is 3.2 mm. The shape and surface quality of the cup are so good that with additional MoS_2 lubrication, the bending stress produced by friction in the gage length of the specimen is negligibly small.

R. Herold, Albertville: The material of the clamping heads is Mo TZM for tests at up to 1800°C. At higher temperature, tantalum alloys with 10% W are used. To prevent the galling of joint threads, the threads are coated with MgO powder.

H. Feldmann: The material of the clamping heads is Mo TZM for tests up to 1800°C, at higher temperatures, tantalum alloy Ta 10 W is used. The drawbars in the furnace are made of TZM molybdenum. Clamping heads are threaded with the drawbars. Galling of the joint threads is prevented by coating the threads with MgO powder.

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